Aromaticity and Tautomerism. Part IV.[1] Free Energy: Enthalpy Correlations for Protonation of Pyridine Bases and Azine *N*-Oxides and Temperature Variation of the H_0 and H_A Acidity Functions

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Thermodynamic parameters for the protonation of nine substituted pyridines and nine azine *N*-oxides are obtained from basicity measurements of the bases at 25, 40, 60, 80, and 90° using the spectrophotometric method. The protonations of both series of bases follow linear ΔH^0–pK_a correlations. The spectrophotometric measurements are also used to assess the temperature variation of the H_0 and H_A acidity functions and the relationship $H_A = mH_0 + C$ is found to be approximately temperature independent.

In studies on the relation of aromaticity with tautomeric equilibria and basicity[1,2] we used linear free energy–enthalpy correlations to determine ΔH^0 for base protonation.[2a] In this field the most comprehensive empirical investigation is that by Arnett's group[3,4] who define ΔH^0 as the difference in calorimetrically measured heats of solution of base in both an acid and a non-polar reference medium. They report similar linear correlations between pK_a and ΔH^0 for protonation of anilines and pyridines in H_2SO_4 [equations (1) and (2)] and a third correlation [equation (3)] which they suggest holds for protonation of both nitrogen and oxygen bases in HSO_3F. In contrast to equation (3), values of ΔH^0 obtained in the main from variable temperature basicity measurements show no simple correlation with pK_a when all base types are included, although linear relations do seem well defined within series of the same base type. Thus Sacconi *et al.*[5] reported a good linear relationship, albeit over a small pK_a range (4·38—6·79), between pK_a and the heat of neutralisation for pyridine and alkylated pyridines [equation (4)], and our group[6] found a correlation for substituted nitroanilines which extends over a range of 14 pK_a units [equation (5)]. The measurements made in the latter study were also used to examine the temperature variation of the H_0 acidity function.[7]

$$\Delta H^0 = 1{\cdot}62\ \mathrm{p}K_a + 17{\cdot}9 \qquad (1)$$

$$\Delta H^0 = 1{\cdot}65\ \mathrm{p}K_a + 20{\cdot}3 \qquad (2)$$

$$\Delta H^0 = 1{\cdot}78\ \mathrm{p}K_a + 28{\cdot}1 \qquad (3)$$

$$\Delta H^0 = 1{\cdot}49\ \mathrm{p}K_a - 2{\cdot}85 \qquad (4)$$

$$\Delta H^0 = 1{\cdot}14\ \mathrm{p}K_a - 2{\cdot}03 \qquad (5)$$

The present paper reports pK_a measurements at five temperatures for nine weakly basic pyridines, six pyridine *N*-oxides and three diazine *N*-oxides (second protonation). The results are used (i) to extend the pK_a–ΔH^0 correlation for pyridines over a wider range of basicity, (ii) to seek a pK_a–ΔH^0 relationship for the *N* oxides, (iii) to test the generality of the previously reported temperature variation of the H_0 acidity function, and (iv) to investigate the temperature variation of the H_A acidity function. During this study several relevant papers appeared; thus Mosher *et al.*[8] re-examined the protonation of alkylated pyridines by n.m.r. and obtained results in reasonable agreement with those of Sacconi *et al.*,

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[1] Part III, M. J. Cook, A. R. Katritzky, P. Linda, and R. D. Tack, *Tetrahedron Letters*, 1972, 5019.

[2] (*a*) M. J. Cook, A. R. Katritzky, P. Linda, and R. D. Tack, *J.C.S. Perkin II*, 1972, 1295, (*b*) 1973, 1080.

[3] E. M. Arnett, R. P. Quirk, and J. V. Burke, *J. Amer. Chem. Soc.*, 1970, **92**, 1260.

[4] E. M. Arnett, R. P. Quirk, and J. W. Larsen, *J. Amer. Chem. Soc.*, 1970, **92**, 3977.

[5] L. Sacconi, P. Paoletti, and M. Ciampolini, *J. Amer. Chem. Soc.*, 1960, **82**, 3831.

[6] P. D. Bolton, C. D. Johnson, A. R. Katritzky, and S. A. Shapiro, *J. Amer. Chem. Soc.*, 1970, **92**, 1567.

[7] C. D. Johnson, A. R. Katritzky, and S. A. Shapiro, *J. Amer. Chem. Soc.*, 1969, **91**, 6654.

[8] M. W. Mosher, C. B. Sharma, and M. R. Chakrabarty, *J. Magnetic Resonance*, 1972, **7**, 247; M. R. Chakrabarty, C. S. Handloser, and M. W. Mosher, *J.C.S. Perkin II*, 1973, 938.

Bellobono and his co-workers measured the thermodynamic parameters for the protonation of amino-, cyano-, bromo-,[9] and nitro-pyridines,[10] and Klofutar and his co-workers[11,12] investigated the protonation of a number of alkylated pyridine *N*-oxides, reporting a linear correlation between the basicities of *N*-oxides and their corresponding pyridine bases.[11]

EXPERIMENTAL

Materials.—Commercial AnalaR grade sulphuric and hydrochloric acids were used without further purification. The indicators used are listed in Table 1. Indicators (6)—(9) were generously donated by Dr. M. B. Green and (15) by Professor H. Suschitzky. Other indicators were obtained commercially or made by standard procedures. All were repurified to give physical constants which agreed with accepted literature values.

TABLE 1

Physical constants of indicators

Indicator	M.p. or b.p. (°C)	Lit. m.p. or b.p. (°C)
(1) 3-Chloropyridine	148—149	148—149 [a]
(2) 2-Chloropyridine	168	168 [a]
(3) 2,4-Dichloropyridine	189	189—190 [a]
(4) 2,6-Dichloropyridine	85—87	85—87 [a]
(5) 2-Nitropyridine	71	71 [b]
(6) 2,3,4,5-Tetrachloropyridine	21—22	21—22 [a]
(7) 2-Fluoro-6-chloropyridine	34—36	34—36 [c]
(8) Pentachloropyridine	123—124	123—124 [a]
(9) 2,3,4,5-Tetrachloro-6-fluoropyridine	234	234 [d]
(10) Pyridine 1-oxide	66—67	65—66 [e]
(11) 3,5-Dimethyl-4-nitropyridine 1-oxide	175—176	174—175
(12) 3,5-Dichloropyridine 1-oxide	110—110·5	109—110 [g]
(13) 3,5-Dimethoxy-2-nitropyridine 1-oxide	168—169	169—171 [h]
(14) 2,6-Dichloropyridine 1-oxide	139—140	139—140 [g]
(15) Pentachloropyridine 1-oxide	178	178 [i]
(16) 4-Methylquinazoline 3-oxide (hydrate)	170—172	170—172 [j]
(17) 2,3,5,6-Tetramethylpyrazine 1,4-dioxide	224	224 [k]
(18) Phenazine 5-oxide	226·5	223 [l]

[a] 'Pyridine and its Derivatives, Part Two,' ed. E. Klingsberg, in the series 'The Chemistry of Heterocyclic Compounds,' ed. A. Weissberger, Interscience, New York, 1961, p. 385. [b] A. Kirpal and W. Böhm, *Ber.*, 1931, **64**, 767. [c] W. A. Thomas and G. E. Griffin, *Org. Magnetic Resonance*, 1970, **2**, 503. [d] C. D. S. Tomlin, J. W. Slater, and D. Hartley, B.P. 1,161,492/1969 (*Chem. Abs.*, 1969, **71**, 91,313*j*). [e] *Org. Synth.*, 1953, **33**, 79. [f] J. M. Essery and K. Schofield, *J. Chem. Soc.*, 1960, 4953. [g] Ref. 14. [h] H. J. den Hertog, M. van Ammers, and S. Schukking, *Rec. Trav. chim.*, 1955, **74**, 1171. [i] S. M. Roberts and H. Suschitzky, *Chem. Comm.*, 1967, 893. [j] K. Adachi, *J. Pharm. Soc. Japan*, 1957, **77**, 514. [k] B. Klein and J. Berkowitz, *J. Amer. Chem. Soc.*, 1959, **81**, 5160. [l] G. R. Clemo and H. McIlwain, *J. Chem. Soc.*, 1938, 479.

Preparation of Solutions.—Stock concentrated sulphuric acid, standardised against standard sodium hydroxide using screened methyl orange, was diluted with water as follows. To prepare an X% solution of sulphuric acid $100X\rho/Y$ g of stock acid solution of Y strength was weighed and made up to 100 ml with distilled water. ρ Is the density of X% sulphuric acid at 25°. The solutions thus prepared were standardised (49·04/X in 100 ml) using N/10-sodium hydroxide. For lower acid strengths a method involving specific gravities was used to check the concentrations of acid solutions. The specific gravity was measured on an A.S.E. torsion-type balance, No. 180, and then the acidity read off from a graph of specific gravity *versus* % H_2SO_4.

The indicator stock solutions were prepared by addition of a weighed amount of indicator to a volumetric flask and dissolving this in aqueous sulphuric acid of sufficient strength to protonate it completely (to aid dissolution). 1 ml Of the solution was then taken by a micrometer syringe and made up to 10 ml. This was carried out for all the solutions. The reference solutions were prepared in a similar way to obtain the same strength as the sample.

Spectrophotometric Measurements.—Two matched u.v. grade 1 cm cells (Unicam) fitted with polythene stoppers were used; Teflon stoppers tended to crack the necks of cells. The absorbances were measured on a Unicam SP 500 spectrophotometer, fitted with an electrically thermostatted cell holder and temperature controller (Adkins). The temperature of the sample cell was measured by connecting a thermocouple built in to the stopper of the sample cell. This was then connected to a Scalamp thermocouple galvanometer (Pye). The log I ratios were determined by equation (6) where ε_B, ε_{BH^+}, and ε_{obs} are the

$$\log_{10} I = \log_{10} [(\varepsilon_B - \varepsilon_{obs})/(\varepsilon_{obs} - \varepsilon_{BH^+})] \qquad (6)$$

extinction coefficients of the free base, the conjugate acid, and some mixture of the two, respectively.

RESULTS AND DISCUSSION

Thermodynamic Parameters of Base Protonation.—The pK_a of each base was determined at 25, 40, 60, 80, and 90° using the spectrophotometric method (see Experimental section). Of the pyridine bases, seven were protonated in the H_0 region and their pK_a values were calculated by equation (7): the values of H_0 for different acid strengths at the five temperatures were taken from ref. 7 (see also Table 2). The ionisation ratios for the pyridine bases in different strengths of sulphuric acid are reported in Supplementary Publication No. SUP 20987 (7 pp.).* Plots of $\log_{10} I$ against H_0 (or pH) gave good straight lines with correlation coefficients $r > 0{\cdot}986$. The value of the slope, n, for the pyridines undergoing protonation in the H_0 region were sufficiently close to unity to conclude that the protonation follows the H_0 acidity function at each temperature; the pK_a values at the five temperatures and values of n are reported in Table 3. Table 3 also shows values derived using the overlap procedure (see later). The basicities of the two strongest indicators (1) and (2), 3-chloro- and 2-chloropyridine, decrease on raising the temperature, whereas the reverse is true for the weaker bases; a similar effect was also observed in the earlier work[6] on the nitroaniline series where the transition point occurs at a pK_a of *ca.* −2·40. There appears to be no sequential variation of n with temperature.

$$H_0 = \mathrm{p}K_a - n \log_{10} ([BH^+]/[B]) \qquad (7)$$

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* For details of Supplementary Publications see Notice to Authors No. 7 in *J.C.S. Perkin II*, 1972, Index issue. Items less than 10 pp. are supplied as full-size copies.

[9] I. R. Bellobono and M. A. Monetti, *J.C.S. Perkin II*, 1973, 790.

[10] I. R. Bellobono and E. Diani, *J.C.S. Perkin II*, 1972, 1707.

[11] C. Klofutar, Š. Paljk, and D. Kremser, *Spectrochim. Acta*, 1973, **29A**, 139.

[12] C. Klofutar, Š. Paljk, and B. Barlič, *Spectrochim. Acta*, 1973, **29A**, 1069.

TABLE 2

Values of acidity function at different temperatures obtained from the protonation of substituted pyridines [a]

% H_2SO_4	25°	40°	60°	80°	90°
14	−0·64 (−0·65)	−0·63 (−0·62)	−0·57 (−0·58)	−0·56 (−0·57)	−0·52 (−0·51)
16	−0·77 (−0·78)	−0·76 (−0·76)	−0·69 (−0·71)	−0·69 (−0·69)	−0·63 (−0·63)
18	−0·92 (−0·92)	−0·89 (−0·90)	−0·81 (−0·84)	−0·81 (−0·82)	−0·74 (−0·76)
20	−1·05 (−1·06)	−1·01 (−1·03)	−0·94 (−0·96)	−0·93 (−0·95)	−0·86 (−0·87)
22	−1·19 (−1·20)	−1·14 (−1·16)	−1·07 (−1·09)	−1·08 (−1·08)	−0·98 (−0·99)
24	−1·32 (−1·34)	−1·26 (−1·29)	−1·20 (−1·22)	−1·20 (−1·20)	−1·10 (−1·11)
26	−1·46 (−1·47)	−1·39 (−1·42)	−1·32 (−1·34)	−1·31 (−1·33)	−1·22 (−1·23)
28	−1·59 (−1·60)	−1·52 (−1·56)	−1·44 (−1·46)	−1·43 (−1·45)	−1·34 (−1·35)
30	−1·73 (−1·73)	−1·69 (−1·69)	−1·56 (−1·58)	−1·54 (−1·56)	−1·46 (−1·47)
32	−1·86 (−1·85)	−1·78 (−1·83)	−1·68 (−1·71)	−1·66 (−1·69)	−1·57 (−1·59)
34	−1·99 (−1·99)	−1·91 (−1·96)	−1·80 (−1·83)	−1·76 (−1·80)	−1·70 (−1·72)
36	−2·08 (−2·12)	−2·00 (−2·10)	−1·90 (−1·96)	−1·89 (−1·92)	−1·82 (−1·84)
38	−2·25 (−2·27)	−2·15 (−2·25)	−2·05 (−2·10)	−1·99 (−2·06)	−1·90 (−1·97)
40	−2·43 (−2·42)	−2·32 (−2·40)	−2·23 (−2·25)	−2·17 (−2·21)	−2·07 (−2·10)
42	−2·62 (−2·60)	−2·53 (−2·55)	−2·42 (−2·40)	−2·36 (−2·36)	−2·26 (−2·25)
44	−2·84 (−2·77)	−2·73 (−2·71)	−2·61 (−2·56)	−2·56 (−2·51)	−2·46 (−2·39)
46	−3·01 (−2·95)	−2·92 (−2·86)	−2·82 (−2·72)	−2·76 (−2·67)	−2·63 (−2·55)
48	−3·16 (−3·12)	−3·12 (−3·01)	−2·98 (−2·88)	−2·91 (−2·83)	−2·77 (−2·76)
50	−3·29 (−3·30)	−3·28 (−3·18)	−3·13 (−3·04)	−3·04 (−2·98)	−2·89 (−2·86)
52	−3·42 (−3·48)	−3·41 (−3·34)	−3·27 (−3·20)	−3·14 (−3·14)	−3·06 (−3·02)
54	−3·57 (−3·68)	−3·55 (−3·53)	−3·41 (−3·37)	−3·35 (−3·32)	−3·23 (−3·19)
56	−3·74 (−3·90)	−3·71 (−3·74)	−3·55 (−3·57)	−3·53 (−3·49)	−3·41 (−3·36)
58	−3·96 (−4·13)	−3·87 (−3·95)	−3·71 (−3·77)	−3·73 (−3·68)	−3·59 (−3·55)

[a] Figures in parentheses denote corresponding values determined for the H_0 function (ref. 7).

TABLE 3

p*K* Values for the protonation of substituted pyridines and azine *N*-oxides[a]

Indicator	25°		40°		60°		80°		90°	
	b	*c*	*b*	*c*	*b*	*c*	*b*	*c*	*b*	*c*
(1)	2·83 (0·90)		2·74 (0·92)		2·64 (0·93)		2·56 (0·95)		2·50 (0·96)	
(2)	0·75 (1·00)		0·72 (1·01)		0·69 (0·95)		0·71 (1·00)		0·65 (1·04)	
(3)	−1·26 (1·00)	−1·23	−1·14 (0·99)	−1·09	−1·04 (0·99)	−1·02	−0·96 (0·97)	−0·96	−0·90 (1·03)	−0·94
(4)	−2·57 (0·82)	−2·57	−2·51 (0·75)	−2·48	−2·38 (0·75)	−2·38	−2·23 (0·88)	−2·36	−2·12 (0·79)	−2·28
(5)	−2·63 (1·05)		−2·54 (1·16)		−2·40 (1·11)		−2·39 (1·19)		−2·36 (1·02)	
(6)	−3·21 (1·08)	−3·20	−3·05 (0·91)	−3·14	−2·87 (0·86)	−3·01	−2·83 (0·91)	−2·93	−2·79 (0·94)	−2·84
(7)	−3·69 (0·99)	−3·78	−3·57 (0·99)	−3·72	−3·41 (0·99)	−3·61	−3·25 (0·99)	−3·30	−3·17 (0·99)	−3·20
(8)	−6·09 (1·16)		−5·82 (0·99)		−5·44 (1·06)		−5·26 (1·02)		−5·06 (1·02)	
(9)	−7·71 (0·99)		−7·40 (1·00)		−6·92 (1·00)		−6·59 (0·98)		−6·25 (0·99)	
	d	*c*		*c*		*c*		*c*		*c*
(10)		0·79		0·82		0·85		0·88		0·90
(11)		−0·52		−0·46		−0·44		−0·42		−0·40
(12)		−0·83		−0·75		−0·71		−0·69		−0·68
(13)	−1·75 (0·99)	−1·69		−1·44		−1·43		−1·39		−1·22
(14)	−2·21 (1·00)	−2·11		−1·94		−1·87		−1·78		−1·57
(15)	−2·68 (0·99)	−2·59		−2·41		−2·31		−2·25		−1·97
(16) [e]	−3·63 (0·52)	−3·73		−3·57		−3·42		−3·37		−3·12
(17) [e]	−4·01 (0·61)	−4·56		−4·28		−4·03		−4·13		−3·73
(18) [e]	−4·30 (0·78)	−4·88		−4·55		−4·42		−4·35		−3·88

[a] Figures in parentheses denote ' *n* value.' [b] Using H_0. [c] Overlap procedure. [d] Using H_A. [e] Second protonation.

The basicities of the *N*-oxides at the five temperatures were measured using the overlap method employing pyridine *N*-oxide as the anchoring indicator. The values of $\log_{10} I$ at different acid strengths are given in the Supplementary Publication; * inspection of Figure 1 shows good parallelism between the curves for the pyridine *N*-oxides but the curves for the second protonation of the diazine *N*-oxides, which were originally investigated to extend the study over a greater range of basicity, deviate. Values of pK_a at the five temperatures appear in Table 3: the results for pyridine *N*-oxide agreed to within 0·01 pK_a unit with values obtained in aqueous hydrochloric acid.[13] pK_a Values at 25° obtained by assuming H_A acidity function behaviour [14] are also reported in the Supplementary Publication for comparison.

Thermodynamic parameters for protonation of each base were obtained by plotting pK_a against $1/T$. The plots were linear indicating that ΔH^0 was invariant with temperature within the limits of the experimental error, over the range of temperature measured; values of ΔG^0, ΔH^0, and ΔS^0 are reported in Table 4. The results for 2-nitropyridine differ somewhat from those given by Bellobono and Diani.[10]

TABLE 4

Thermodynamic parameters for the ionisation of substituted pyridines and azine *N*-oxides

Substituted [a] pyridines	ΔG^0_{25}/ cal mol^{-1}	ΔH^0/ cal mol^{-1}	ΔS^0/ cal mol^{-1} K^{-1}
(1)	3680 ± 290	2480 ± 1190	4·70 ± 1·10
(2)	1023 ± 270	775 ± 380	0·83 ± 0·40
(3)	−1705 ± 130	−2611 ± 560	3·05 ± 1·50
(4)	−5304 ± 170	−3405 ± 1920	0·50 ± 0·40
(5)	−3586 ± 535	−2083 ± 2010	3·29 ± 1·60
(6)	−4380 ± 220	−2580 ± 885	5·57 ± 2·85
(7)	−4869 ± 230	−3923 ± 1560	3·78 ± 3·20
(8)	−8305 ± 280	−7653 ± 1080	2·17 ± 1·35
(9)	−10,513 ± 250	−10,808 ± 1640	0·80 ± 0·38
Azine *N*-oxides			
(10)	1080	−793	6·302
(11)	−707 ± 130	−797 ± 70	0·366 ± 0·040
(12)	−1140 ± 40	−1045 ± 260	−0·206 ± 0·030
(13)	−2306 ± 140	−2764 ± 900	1·790 ± 1·46
(14)	−2881 ± 204	−3505 ± 1150	2·124 ± 0·124
(15)	−3534 ± 17	−3900 ± 260	1·200 ± 0·824
(16)	−5085 ± 234	−3960 ± 1160	−3·780 ± 1·212
(17)	−6224 ± 190	−5095 ± 304	−3·574 ± 0·632
(18)	−6660 ± 190	−6083 ± 300	−1·817 ± 0·920

[a] Errors are quoted as ± standard deviation.

pK_a : ΔH^0 *Correlations*.—Figure 2 show a plot of pK_a against ΔH^0 for pyridine bases, incorporating both the present results and those reported in ref. 5. It is apparent that a linear correlation exists for the present series of pyridines and a determination of the best straight line through the points, by the least squares method, gives equation (8) r being 0·987. When the data reported by Sacconi *et al.*[5] are also included, the best straight line is given by equation (9) (r 0·996), a correlation which extends over 14·5 pK_a units.

A similar plot of the data for *N*-oxides is also given in Figure 2. Again there appears to be a linear correlation and the best straight line through the points obtained in the present investigation is given by equation (10) (r 0·958). Unlike the pyridine series where inclusion of literature values does not significantly alter the straight line correlation, we find that equation (10) does not accommodate at all well the data reported by Klofutar

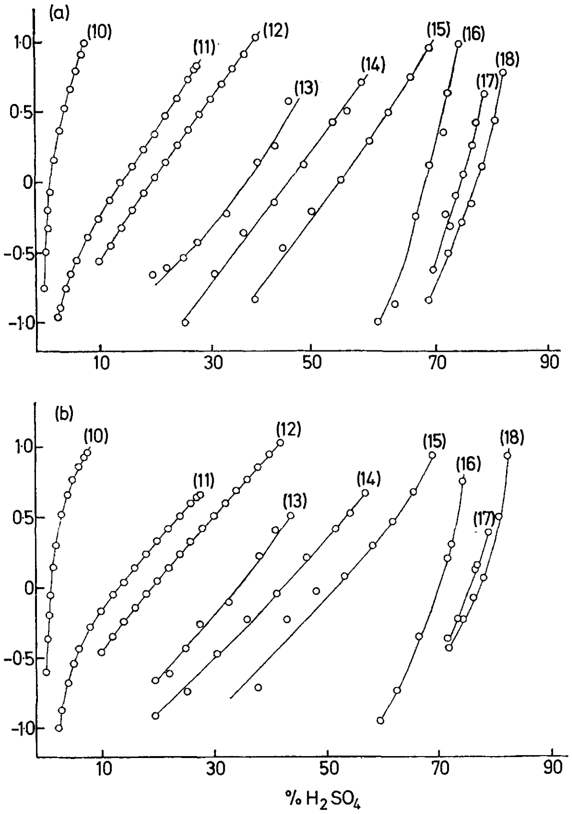

FIGURE 1 Plot of log I *versus* % H_2SO_4 for substituted *N*-oxides at (a) 25°, (b) 90°

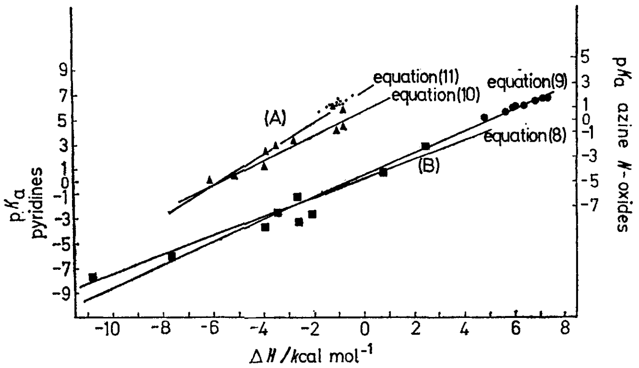

FIGURE 2 Plot of pK_a *versus* ΔH^0 for substituted azine *N*-oxides (A) and substituted pyridines (B): ●, data of ref. 5; ▲, ■, present work, data of refs. 11 and 12

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* Same footnote as on page 1070.

[13] For details see T. W. Toone, Ph.D. Thesis, University of East Anglia, 1972.

[14] C. D. Johnson, A. R. Katritzky, and N. Shakir, *J. Chem. Soc.* (*B*), 1967, 1235.

et al.[11,12] the best line drawn through all the points is given by equation (11) (r 0·942).

$$\Delta H^0 = 1{\cdot}25\ \mathrm{p}K_a - 0{\cdot}338 \tag{8}$$

$$\Delta H^0 = 1{\cdot}11\ \mathrm{p}K_a - 0{\cdot}638 \tag{9}$$

$$\Delta H^0 = 1{\cdot}04\ \mathrm{p}K_a - 0{\cdot}79 \tag{10}$$

$$\Delta H^0 = 0{\cdot}78\ \mathrm{p}K_a - 1{\cdot}81 \tag{11}$$

It is evident that the slopes of the ΔH^0–pK_a correlations for nitroanilines and pyridines are very similar, and the similarity extends also to the line for the present series of azine *N*-oxides. The slope parameters however differ somewhat from those reported by Arnett's group,[3,4] but the assumptions inherent in the two approaches are quite different.

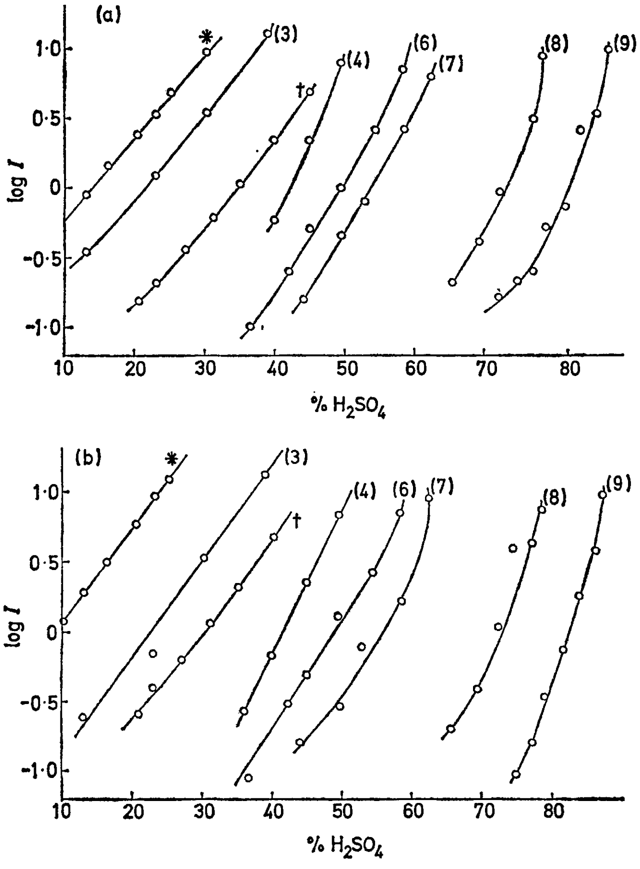

FIGURE 3 Plot of log *I versus* % H_2SO_4 for substituted pyridines at (a) 25°, (b) 90°; * 4-nitroaniline, † 2,5-dichloro-4-nitroaniline (see text)

Temperature Variation of the H_0 *Acidity Function.*—The experimental data obtained in the present work allows a partial investigation of the temperature variation of the acidity function for pyridine protonation. As was apparent from the discussion above, pyridine protonation closely follows the H_0 acidity function and therefore such a study allows an assessment of the generality of the earlier results obtained in this laboratory[7] for the temperature variation of H_0. The values of $\log_{10} I$ for each indicator were plotted against percentage sulphuric acid and smooth curves drawn through the points. Figure 3 shows the series of curves obtained at 25 and 90°; similar plots were also obtained for the data obtained at 40, 60, and 80°. As the pK_a of the anchoring indicator should be determined in hydrochloric acid solution 4-nitroaniline was chosen as much data are available for this base. Overlap between indicators (3) and (4) was improved by the inclusion of data for 2,5-dichloro-4-nitroaniline, whilst the absence of any overlap between (7) and (8) enforced the curtailment of the investigation at 58% H_2SO_4. The calculation of the acidity function at the five temperatures was carried out according to the method described in ref. 7, and values are reported and compared with the previous data for the H_0 function in Table 2. There is a good correspondence between the two series of values which verifies that protonation of the pyridine bases indeed follows the H_0 acidity function at each of the temperatures investigated; the data also support the generality of the previous results. As would be expected, pK_a values derived from the present overlap procedure correspond closely with those obtained using the H_0 function (Table 3).

Temperature Variation of the H_A *Acidity Function.*—Previous work from this laboratory established that the protonation of pyridine *N*-oxides[14] follows closely the H_A acidity function, which was defined originally by the protonation of substituted benzamides.[15] In view of difficulties to be expected from amide hydrolysis at elevated temperatures it seemed appropriate to use the present data for *N*-oxides for investigating the temperature variation of the H_A acidity function. Good overlap and parallelism of the log *I* plots are essential requirements and inspection of Figure 1 reveals that these are fulfilled among the series of pyridine *N*-oxide indicators (10)—(15), but parallelism between these indicators and the diazine *N*-oxides (16)—(18) is less than ideal. However, obtaining suitable pyridine *N*-oxides, *i.e.* pyridine *N*-oxides more weakly basic than pentachloropyridine 1-oxide (15), presents a preparative problem and we believe that the use of the diazine *N*-oxides is an acceptable compromise at the present time. The calculation of the acidity function at the five temperatures was performed as described in ref. 7 and values are reported in Table 5. As before,[7] at particular acid strengths plots of log *I* against $1/T$ were straight lines and accordingly the temperature variation of the H_A function can be expressed by equation (12) and hence equation (13) where K is $(\alpha + A)$ and L is $(\beta + B)$. H_A Values at concentration intervals of 2% were plotted against $1/T$ and the constants K and L (Table 6) were evaluated using a least squares program.

$$\begin{aligned} H_A(T) &= \log I\,(T) + \mathrm{p}K_a\,(T) \\ &= \alpha/T + \beta + A/T + B \end{aligned} \tag{12}$$

$$H_A(T) = K/T + L \tag{13}$$

[15] K. Yates, J. B. Stevens, and A. R. Katritzky, *Canad. J. Chem.*, 1964, **42**, 1957.

Comparison of Temperature Variation of Acidity Functions.—The H_A acidity function decreases in acidity with increasing temperature, a phenomenon which has also been observed for the H_0 [7] and H_R [13,16] acidity functions (but contrast ref. 17). Previously it was shown [7] that plots of H_R *versus* H_0 gave good straight lines over the 25—45° temperature range but the slope parameter, *m*, varied with temperature showing that the relationship [equation (14)] observed to hold [18] at one temperature does not hold at others. By contrast, we now find from similar treatment of data for H_A and H_0 that neither *m* nor the intercept parameter *C*, vary substantially over the temperature range 25—90° (Table 7). As would be expected, on this basis, the slope parameter for plots of H_R [16] *versus* H_A at different temperatures was found to vary significantly: *m* 2·92 (25°), 2·90 (40°), 2·67 (60°), 2·31 (80°), 2·34 (90°).

TABLE 5

Values of the H_A acidity function at different temperatures obtained from the protonation of azine *N*-oxides

	H_A				
% H_2SO_4	25°	40°	60°	80°	90°
2	0·626	0·628	0·609	0·635	0·610
4	0·252	0·267	0·264	0·252	0·251
6	0·019	0·048	0·044	0·034	0·044
8	−0·143	−0·091	−0·098	−0·109	−0·119
10	−0·264	−0·193	−0·190	−0·224	−0·239
12	−0·381	−0·318	−0·324	−0·334	−0·344
14	−0·511	−0·439	−0·433	−0·447	−0·443
16	−0·632	−0·560	−0·543	−0·547	−0·543
18	−0·752	−0·675	−0·656	−0·648	−0·643
20	−0·862	−0·789	−0·765	−0·747	−0·737
22	−0·980	−0·902	−0·871	−0·847	−0·823
24	−1·099	−1·007	−0·965	−0·947	−0·851
26	−1·219	−1·118	−1·060	−1·039	−0·934
28	−1·286	−1·221	−1·153	−1·127	−1·014
30	−1·377	−1·271	−1·248	−1·213	−1·091
32	−1·457	−1·368	−1·347	−1·313	−1·169
34	−1·550	−1·472	−1·452	−1·408	−1·231
36	−1·663	−1·578	−1·559	−1·509	−1·322
38	−1·800	−1·682	−1·671	−1·608	−1·412
40	−1·907	−1·787	−1·771	−1·696	−1·499
42	−2·035	−1·896	−1·867	−1·790	−1·594
44	−2·123	−1·959	−1·940	−1·842	−1·648
46	−2·233	−2·055	−2·032	−1·932	−1·733
48	−2·332	−2·146	−2·123	−2·021	−1·817
50	−2·442	−2·241	−2·212	−2·116	−1·994
52	−2·542	−2·345	−2·305	−2·205	−2·080
54	−2·642	−2·437	−2·394	−2·302	−2·077
56	−2·762	−2·543	−2·485	−2·404	−2·246
58	−2·870	−2·653	−2·591	−2·510	−2·320
60	−2·986	−2·771	−2·679	−2·609	−2·384
62	−3·048	−2·869	−2·745	−2·704	−2·412
64	−3·177	−3·010	−2·868	−2·829	−2·534
66	−3·364	−3·174	−3·030	−2·977	−2·683
68	−3·654	−3·145	−3·252	−3·178	−2·905
70	−4·001	−3·702	−3·471	−3·447	−3·170
72	−4·272	−3·971	−3·779	−3·727	−3·426
74	−4·494	−4·186	−3·986	−3·986	−3·593
76	−4·734	−4·414	−4·195	−4·216	−3·764
78	−4·964	−4·665	−4·432	−4·436	−3·910
80	−5·259	−4·925	−4·678	−4·600	−4·200

Implications for the Estimation of Aromatic Resonance Energies.—Our estimation [1,2] of aromatic resonance energies using tautomeric and protonation equilibria require ΔH^0 values rather than ΔG^0 data and the following relationships were used to convert ΔG^0 (or pK_a) data into

$$H_X = mH_0 + C \qquad (14)$$

$$\Delta H^0 = 1{\cdot}32\,\Delta G^0 - 0{\cdot}85 \qquad (15)$$

ΔH^0 data: (i) Hepler's derivation that ΔG^0 is a good estimate for ΔH_{int}, a simplification of an expression $\Delta G^0 = \Delta H_{\text{int}}(1 + \gamma)$ where γ is a solvent dependent parameter,[19] (iia) the nitroaniline correlation equation (5), (iib) a combination of the nitroaniline correlation and the pyridine correlation of Sacconi *et al.*,[5] (iii) equation (3) obtained by Arnett's group,[4] and (iv)

TABLE 6

The values of the constants *K* and *L* in the expression $H_A/(T) = K/T + L$ as defined by substituted *N*-oxides

% Acid	$-(K \times 10^{-3})$	$-L$
2	−0·024	−0·552
4	−0·001	−0·240
6	0·039	−0·136
8	0·066	−0·071
10	0·064	0·062
12	0·083	0·111
14	0·119	0·123
16	0·165	0·087
18	0·182	0·145
20	0·214	0·154
22	0·253	0·137
24	0·318	0·022
26	0·399	0·121
28	0·339	0·123
30	0·368	0·135
32	0·345	0·287
34	0·351	0·348
36	0·372	0·383
38	0·442	0·290
40	0·488	0·244
42	0·529	0·277
44	0·589	0·118
46	0·630	0·091
48	0·640	0·146
50	0·639	0·288
52	0·661	0·317
54	0·732	0·163
56	0·726	0·324
58	0·749	0·348
60	0·822	0·223
62	0·806	0·321
64	0·826	0·385
66	0·878	0·399
68	0·931	0·528
70	1·225	−0·087
72	1·203	0·240
74	1·204	0·456
76	1·269	0·478
78	1·328	0·495
80	1·459	0·355

TABLE 7

Results from plots of $H_A(T)$ *versus* $H_0(T)$

	25°	40°	60°	80°	90°
Slope	0·68	0·69	0·68	0·70	0·65
Intercept	−0·10	−0·02	−0·05	−0·03	−0·09
r	0·996	0·996	0·996	0·996	0·996

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equation (15) derived from tautomeric equilibrium data for a number of substituted pyridines.[20] The linear relationships between pK_a and ΔH^0 for nitroanilines [equation (4)], pyridines [equation (9) and (8)], and pyridine *N*-oxides [equation (10)] and the close agreement in the slopes of the plots is encouraging and enhances our confidence in the conversion of pK_a data directly into ΔH^0 values, and suggests further that results obtained by method (iia) may be the most satisfactory for our purposes.

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[3/2618 *Received*, 28*th December*, 1973]

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